

# **UPDATE OF ASSESSMENT OF GEOTECHNICAL RISKS, STRATEGIC PETROLEUM RESERVE, WEEKS ISLAND SITE**

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## **Abstract**

This report is a critical reassessment of the geotechnical risks of continuing oil storage at the Weeks Island Strategic Petroleum Reserve site. It reviews all previous risk abatement recommendations, subsequent mitigative actions, and new information. Of increased concern, due to the discovery of a surface sinkhole and the conclusion that the sinkhole is due to water entry into the oil storage levels, is the long term maintainability of the mine as an oil storage repository. Mine operational changes are supported in order to facilitate monitoring of water entry diagnostics. These changes are also intended to minimize the volume in the mine available for water entry. Specific recommendations are made to implement the mine changes.

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# UPDATE OF ASSESSMENT OF GEOTECHNICAL RISKS STRATEGIC PETROLEUM RESERVE WEEKS ISLAND SITE

## EXECUTIVE SUMMARY

This report is an update of the current geotechnical status, risks, and concerns of the Weeks Island (WI) Strategic Petroleum Reserve oil storage site. This report updates a 1985 study which had identified concerns associated with the potential for underground failure of existing shafts and mined openings. The 1985 study recognized that such a failure would have led to uncontrolled solutioning around the bulkheads isolating the accessible **manways** above the oil storage from the two previously - mined oil storage levels. Following the study, new bulkhead construction was undertaken, existing systems were upgraded, and new withdrawal and monitoring capabilities were developed to directly address the concern raised in the study. In 1992 a surface sinkhole was discovered over the southern edge of the mine. By late 1993 the size of the sinkhole had begun, to increase measurably, and an increase in brine **inflow into** the mine was detected. The initial phase of a major diagnostic effort was completed to identify the cause of the sinkhole, and develop possible mitigative options, if necessary.

The diagnostics effort was successful in locating a significant leached zone or crevasse in the salt below the sinkhole and measuring the downward flow of partially saturated brine and sediments well below the top of salt. Simultaneously, the brine inflow into the fill holes area in the mine was significantly increasing in concert **with** the volume of fill material **being** used to fill the sinkhole at the surface. Since early 1992 the isotopic composition of brine in the fill holes has been evolving toward that of ground water sampled over the salt dome. The evidence was sufficient to conclude that the sinkhole is due to sediment subsidence into voids created by salt dissolution from ground water flow into the mine.

Recent geomechanics simulations of WI indicate the salt zones above the outer mine boundaries to be in tension, from which dilation or increased permeability (possibly cracking) may follow. Modeling of a simulated fissure into the mine with sand **fill** in the available dissolutioned volume suggests that the current sinkhole volume might represent an ongoing leak taking many years to develop. Such modeling indicates that a leak may increase 10 fold in 5 years if unmitigated.

Diagnostic measurements in the form of geotechnical investigations (geologic, geophysical, and hydrologic) have been completed which indicate the following: (1) the sinkhole is a surface expression of nearly vertical chimney(s) or crevasse(s) in the top of salt into which overlying sediment has flowed, (2) the geometry of a funnel/chimney-like sediment filled feature has been estimated through surface geophysics and crosswell tomography, (3) sediment is currently estimated to be flowing downward at about 1 inch/day, (4) water in that sediment is flowing

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~~predominantly downward~~ at approximately 1 foot/day, (5) water in the sump is becoming ~~more connate~~ with time, and (6) there appears to be a direct connection between injection of brine into the crevasse below the sinkhole and surface displacement (enlargement) of the sinkhole. Current mine leak diagnostics indicate an increased brine accumulation but have not yet detected dye injected into the downward flowing brine near the top of salt and in the subsurface below the sinkhole.

Considering the existence and location of the sinkhole and the associated leak, the geomechanics modeling, the experience of a similar mine, the limitations of the **geotechnical** and mine diagnostics, and the mitigative options available, there is real concern over the long-term viability of continued oil storage at Weeks Island. There is no historical experience either successful or unsuccessful of attempted long-term storage of oil (or other fluids) under these conditions. Based on the experience of others with leaking mines, stopping water entry over the long term is anticipated to be extremely difficult, if not impossible. Initial efforts at leak control are encouraging which provide near term confidence in continued operations. Long term operation is anticipated to become more difficult with the possibility for additional leaks and their cost implications, although accurately predicting the timing of future leaks is impossible.

The leak increases the concern of maintaining total control of oil during normal drawdowns. Of major consequence during a normal **drawdown** would be the washout of permeable overburden material in the leak path which may be limiting rapid salt solutioning and high-volume water inflow. The likelihood of such an event may be quite low but the consequences would be extremely serious if sufficient water is available in the saturated zone above the salt to greatly increase the dimensions of the leak path through dissolutioning, and saturate or prevent operation of the mine withdrawal pumping capacity. Increased pressurization of the mine, development of a raw water **or** brine source, and the adaptation of the withdrawal system to accommodate maintenance of a liquid-filled mine during withdrawal is an approach that will minimize potential consequences under any conditions, but it is a more complex oil withdrawal method.

In order to evaluate the consequences of a washout during a normal drawdown, and investigate other seismic anomalies and possible leak detection techniques, an ongoing diagnostics program has been approved and its current results are described very briefly,

## INTRODUCTION

Geotechnical concerns associated with oil storage at Weeks Island were first assessed in a 1985 study. At that time experience with continued brine/water leaks associated with the shafts into the accessible drifts above the storage levels, and into the Wet Drift area had generated concern over continued long term storage. In response to the study and subsequent analyses, the **SPR** program undertook the construction of two new bulkheads, upgraded several existing bulkheads, developed an emergency withdrawal **capability** and greatly enhanced their surveillance and monitoring capabilities and program. Additionally, many analyses were completed which addressed issues or concerns. As a result of the work, all previously identified concerns with continued oil storage identified in the 1985 study were dispelled.

Since 1985 two events have occurred that in retrospect appear related, and which at the time raised concerns. In 1987, a significant quantity of brine (over 40 Kbbbl was found in the mine in the area of the fill holes. The resulting investigation was inconclusive as to the significance or source of the brine due to the possibility that the brine was the result of water disposed of in the mine following pipeline testing, and/or water associated with the bottom sediments and water (**BS&W**) fraction within the oil. The conclusion did prompt continual monitoring of brine in the fill hole area with the conclusion that an increase in brine flow into the fill hole area was probably an indication of a water leak.

In 1992, a surface sinkhole over the south edge of the mine was discovered. The sinkhole had existed for a period of time but was not an old feature. At that time, the sinkhole appeared stable in size, hence a “wait and watch” approach was adopted. By mid 1993, evidence of sinkhole enlargement began to appear, and the program initiated an investigation as to the source and significance of the sinkhole. By March of 1993, enough information was available to conclude that there was some likelihood that the sinkhole was a result of a leak into the mine. Actual drilling and **downhole** seismic diagnostic data acquisition were undertaken in June ~~1993~~<sup>1994</sup>, resulting in the current conclusion that there is a leak into the mine, and the sinkhole is a result of salt dissolution by water associated with the leak into the mine. Further, the brine inflow in the fill holes in all probability also results from a leak into the mine.

In an attempt to understand the significance of the leak and possible future implications, modeling of leaks has been completed, and the experiences of other mine operators have been sought. Additionally, leak mitigative efforts have been initiated by the site operations (specifically brine injection), along with contingency planning, and further diagnostics effort definition.

This report recognizes the work that has been done in earlier mitigative efforts, references the major analytic efforts, and summarizes recent diagnostic information learned while investigating the sinkhole. Additionally it identifies the concerns associated with a leak and possible **future** mitigative options.

# 1. REVIEW OF PRIOR WEEKS ISLAND RISK ASSESSMENT

A report describing the results of an evaluation of risks to continued safe oil storage at the Weeks Island Strategic Petroleum Reserve facility was published in June 1985 by Sandia National Laboratories (**Beasley** et al, 1985). It identified five major areas of risk that were believed to jeopardize oil storage at Weeks Island. The five major risk locations were:

1. **Wet Drift**
2. Production Shaft
3. Service **Shaft**
4. Markel mine
5. Vent and fillholes

In addition to identifying these risk areas, the report described four essential activities for risk reduction, which were:

1. Inspections
2. Emergency grouting
3. Protection of the oil withdrawal capability
4. Construction of isolation bulkheads and shaft liners

Significant progress has been made to alleviate or mitigate the then identified major risks to continued safe oil storage at Weeks Island. Weekly inspections and findings in the Production Shaft, Service Shaft and the Wet Drift are performed and documented in a weekly report. Semi-annual inspections by an independent grouting engineering contractor are performed and documented. Extensive grouting in the Wet Drift, Production **Shaft** and Service Shaft has taken place. An emergency grouting plan and contract are in place. Construction was completed in 1992 to provide oil withdrawal **capability** from the fillholes should it be necessary to do so. In addition to this project, integrity tests have been performed in the vent and fillholes and an interface detector has been installed in the west fillhole. The abandoned commercial Markel Mine has been isolated with the construction of two concrete bulkheads, and the oil isolation bulkheads have been evaluated for capability to contain hydrostatic pressure should a leak develop into the storage chamber. Three of the oil isolation bulkheads were upgraded to ensure their ability to withstand this pressure.

The report provided **fifteen** risk abatement recommendations. The four recommendations which were considered most urgent to undertake were:

1. Continue monitoring and inspection of the DOE mine and shafts,
2. Develop and implement emergency grouting program,
3. Monitor water leaks in the Wet Drift and other areas, and
4. Protect the oil withdrawal capability.

The site mining engineer performs a weekly visual inspection of the Service Shaft, Production Shaft, and all accessible mine areas. He prepares a report weekly of the findings and changes in oil and brine level measurements. Site Operations performs a daily

underground check including monitoring gas pressures on the oil side of the Service Shaft, Raisebores #1 and #2, Production Shaft, and Markel Incline bulkheads, and in the vent hole. This daily monitoring also includes the oil/brine interface level in the Service **Shaft** and manually strapping the oil/gas interface at the Service Shaft. These data are reported in the Weeks Island Readiness Report. A program and subcontracts with Rembco Engineering Corporation (standby grouting contractor) and Dynatec Mining Corporation (grouting engineer) are in place to perform semiannual inspections of the **manways** and mine **shafts**. Routine inspections of the Markel Mine were discontinued in 1989 due to safety concerns of the conditions in the mine.

Inspection and monitoring of the vent and tillholes with casing caliper instruments and a **borehole** televiewer have not been performed. The east and west fillholes are equipped with 4-1/2" logging casing for running instruments on electric wirelines to measure the brine interface depth. Presently, a capacitance-type interface detector is suspended in the west **fillhole** for continuous monitoring. Comprehensive monitoring and inspection processes are in-place and capable of providing early warning of changes or problems.

An emergency grouting program and a standby grouting contract, which is renewed annually, are in place (Emergency Grouting Program, 1984). The standby grouting subcontractor at present is Rembco Engineering Corporation. Additional grouting engineering support is provided by Dynatec Mining Corporation. Specific grouting procedures have been developed, as well as grouting criteria, which are documented in the standby grouting contract.

Brine accumulation monitoring is performed in the Wet Drift, Service Shaft, and other areas of the mine and reported weekly. Independent overview is performed and reported by the standby grouting subcontractor and the grouting engineering subcontractor during semi-annual inspections.

The "Emergency **Drawdown** System" project (**WI-MM-079B**), completed in 1992, provides an alternative means of recovering oil from the storage caverns in event of flooding of the manifold room or any other event that may render the manifold room pumps inaccessible. Piping, valving and pumping configuration changes and additions have been made to withdraw oil through the **fillholes**.

Progress has been made towards implementing eight additional risk abatement recommendations which were considered of lesser urgency. These eight recommendations and their current status are:

1. Monitor surface subsidence, (ongoing)
2. Investigate shear zones and geometry, (ongoing)
3. Sample water and test, (ongoing)
4. Measure brine in sumps, (ongoing)
5. Collect condensation data and analyze, (ongoing)
6. Perform dimensional surveys of Wet **Drift**, Markel Incline, shafts and associated drifts, (ongoing)
7. Expand sediment, salt and geohydrology study, and (partially completed)
8. Measure mine convergence, (ongoing in the **manways**, but not in Markel Mine).

The SPR Management and Operating contractor (**DynMcDermott**) has overall responsibility for the subsidence program. Included are: identification of need and construction of new monuments, maintenance of existing monuments, providing adequate surveying specifications, subcontracting surveying services, and analysis and reporting of survey results. Survey results are published in the annual subsidence report.,

A detailed surface subsidence monitoring program of the Weeks Island salt dome was developed (PB-KBB, **1986**) under contract with Boeing Petroleum Services. The purpose of the program was to provide a plan to identify, quantify and predict surface and underground subsidence as a partial solution to the risk assessment recommendation pertaining to monitoring surface subsidence. Eighty-two surface subsidence monitors and eight deep monitors and inclinometers have been installed based on the PB-KBB recommendations.

Shear zones and geometry were investigated (Acres International Corporation, 1987) in a detailed geologic site characterization of the Weeks Island salt dome under contract with Sandia National Laboratories. The three principal areas covered by this study were:

1. Stratigraphy and lithology of the sediments adjacent to the dome,
2. Structure within the sediments adjacent to the dome, and
3. Geometry and structure of the salt dome.

Water samples **from** the mine are collected and analyzed at random times. Samples have always been meteoric in origin. Heavy stable isotopic analysis were performed between 1987 and 1990 (Arizona State University, 1990). The present method of monitoring for brine influx into the mine **utilizes** brine/oil interface instruments in probe holes in the Service Shaft bulkhead, and a brine/oil interface monitor in the west **fillhole**. The total fluid in the mine is obtained **from** a manual strapping of the oil/gas interface in the Service **Shaft**. This strapping was replaced by a new automatic instrument in May 1994. Additionally, a second instrument for continuous monitoring of brine in the fillholes was installed in the east **fillhole** in May 1994.

An attempt was made to collect and analyze condensation data in the Production Shaft. Humidity readings near 100 percent precluded meaningful data collection. A mine air treatment system was subsequently installed to dehumidify the air in the Production Shaft. The recommendation was to install continuous read-out instrumentation measuring wet and dry bulb temperatures at the top of the Production and Service Shafts; this was largely negated by the air dryer system.

The recommendation to perform dimensional surveys of the Wet **Drift**, Markel Incline, shafts and associated drifts was substantially completed (**Freyou, 1986**), although new surveys may need to be performed. The Weeks Island Production **Shaft** was surveyed in 1988 (PB-KBB, 1990) and resurveyed in 1990. No analysis has been performed.

The response to the recommendation to expand sediment, salt and geohydrology studies is incomplete. A report summarizing the stratigraphy, soil and salt properties over the Weeks Island dome was completed (Acres International Corporation, 1987) under contract with Sandia National Laboratories. The recommendation also called for

determining the degree of fracturing and fissuring of the upper part of the salt; predictions of the maximum rate of water inflow into breaches in the dome; and development of a detailed knowledge of the Pleistocene and Recent sediments overlying the dome; due to the very significant efforts required and the perceived importance, these were not undertaken.

A monitoring program with Morton to accurately measure convergence in the new Morton Mine, Markel Mine, and associated drifts has not been initiated. Monitoring equipment has been installed in the DOE mine or **manways**, and baseline data collection has begun.

Three risk abatement recommendations of lesser urgency which have yet to be undertaken are:

1. Monitor oil/gas drilling around the dome,
2. Seal well **#16**, and
3. Monitor Morton blasting.

The Louisiana Department of Natural Resources monitors oil and gas drilling around the dome. Reviewing and monitoring all subsurface drilling, brining, and other associated activities, as recommended has not been rigorously pursued due to the general low level of activity around the dome and the perceived cost/benefit. The only ongoing brining at Weeks Island is conducted by Morton Salt Co. in two small caverns. An attempt is planned to locate the coordinates of well **#16**; further work is dependent upon the results of the search. The entire area where the well may be located is heavily wooded; clearing to access the well is severely limited because the area is an endangered species habitat. Although monitoring Morton's blasting procedures was recommended, the cost/benefit could not be supported.

Listed are the specific recommendations which were already completed or withdrawn by the time the earlier risk assessment study was completed:

1. Construct bulkhead in Wet Drift. (completed)
2. Remove dry side steel bulkhead in the Wet Drift to facilitate leak detection. (completed)
3. Fill Wet Drift with brine. (withdrawn)
4. Study possibility of forming a **caprock**. (withdrawn)

## 2. NEW INFORMATION

During the period (1985-1993) following the earlier Weeks Island Risk Assessment the SPR Program has initiated and taken responsive actions in several other geotechnical areas.

1. Designed and built two massive underground bulkheads to isolate the DOE **manways** or drifts above the oil storage levels from the Markel Mine.
2. Completed extensive analyses of the structural capabilities of the five **downhole** oil isolation bulkheads.
3. Designed and completed structural upgrades for the two raisebores and Service **Shaft** bulkheads.
4. Identified and analyzed a significant quantity of brine in the fillholes below the oil. Developed and implemented an ongoing plan for monitoring and removing brine in the fillholes below the oil storage.
5. Completed the design and construction of an air dryer system for removing water from the **manways** ventilation air.

The first responsive action addressed the earlier identified concern of uncontrolled water entry into the **manways** above the oil storage levels causing significant dissolution and erosion around the existing bulkheads and loss of withdrawal capability. Additionally, the upgrades to the existing bulkheads address the concern of bulkhead adequacy to pressure exerted from below, i.e., the oil storage chambers. The air dryer system was recommended in the earlier risk assessment work to eliminate the masking of incipient leaks, and further solutioning in the shafts and **manways** by water condensation from the ventilation system.

Most notable during the period, two additional events occurred:

1. Brine was discovered in the fillholes, initiating additional investigations, and
2. A sinkhole was discovered over the edge of the mine.

In 1987 a sizable quantity of brine was discovered in the **fillhole** sump. The brine was analyzed by radiochemistry methods and tentatively concluded to be meteoric, i.e., basically surface connected water in origin. Additional investigation identified the potential sources of the water as possibly attributable to the Weeks Island pipeline pressure testing (hydrotesting). An additional source of water was part of the **BS&W** (bottom sediment and water) contained within the purchased oil. With the quantity of meteoric water known to be in the mine, no conclusion was possible regarding mine leakage.

The existing brine in the sump was pumped out and monitoring instrumentation installed to monitor any new influx into the **fillhole** sump area. Over the next few years, the rate of influx into the **fillhole** continued to decline but then recently the rate of influx increased, as shown in Figure 1b. In order to understand the effect that oil circulation exercises appeared to have on the brine in the **fillhole** sump, a scale model of the **fillhole** area was constructed at Louisiana State University (Louisiana State University, 1990), and oil circulated as occurs during recirculation exercises. Modeling results indicated clearly

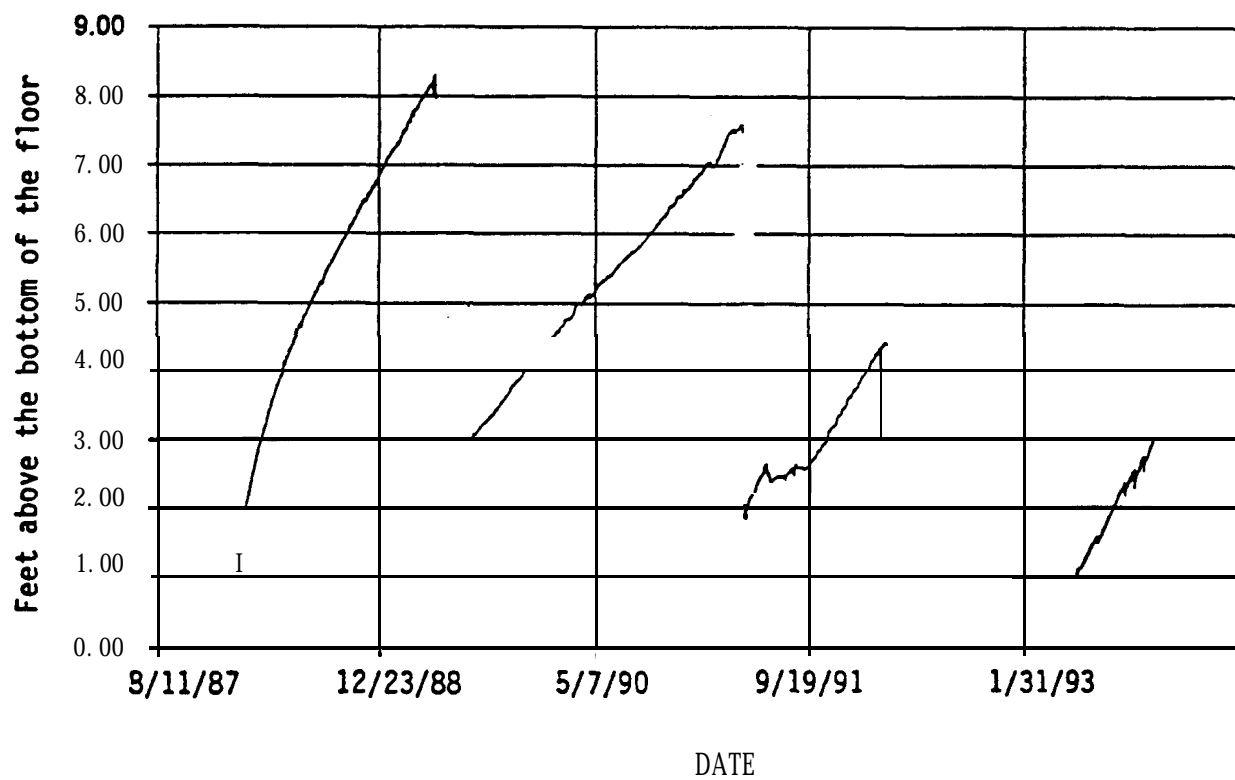


Figure 1a. Brine influx into fill hole sump area.

WEEKS ISLAND FILL HOLE SUMP



that as the flow rate of oil into the **fillhole** increases, interaction of the oil and brine occurs forming an emulsion. The emulsion easily transports brine **from** the fillhole sump into the mine. Over time such brine eventually leaves the emulsion and migrates to the floor of the mine. Brine return to the **fillhole** sump could be delayed or might not occur, depending of the quantity of oil circulated, the exact grading of the mine floor, and the cut “channels.” Consensus of the Weeks Island Risk Abatement Committee and Site Operations had been that a decreasing brine influx rate was indicative of existing water migration into the **fillhole** sump, and not indicative of water **from** leakage into the mine migrating to the sump. Interpretation of inflow into the **fillhole** sump is summarized in Section 2.2.1 and Appendix 1 for the time period following these previous investigations.

The other notable event which took place since the 1985 report was the appearance of a sinkhole over the upper level of the oil storage chamber. The sinkhole was first noticed in May 1992 and has progressively grown since its discovery. The discovery of the sinkhole and follow on work to learn its genesis have prompted this risk re-evaluation.

## **2.1 SINKHOLE**

### **2.1.1 Sinkhole Development**

On May 18, 1992, a security guard working for the SPR incidentally stumbled across the large, steep-sided and deep depression (now identified as the sinkhole) very close to the main access road to Morton Salt and DOE facilities at Weeks Island. The hole was in proximity to a mowed apron, but had evidently previously not been observed. The hole received immediate attention as a safety hazard, and was examined and identified as a sinkhole by Neal and Magorian on the 19th of May. There was an original assumption that it was a dissolution feature as a result of water/salt interaction at the top of salt. This is common over many salt bodies, both domal and bedded. The sinkhole appeared to be stable in size for about a year even though some change of shape occurred continually due to precipitation and side sloughs. By the early part of 1993, it was recognized that the hole was enlarging. Surveys show it to be increasing in size by about 20 cubic yards/month (Figure 2). A very complete geological description of the sinkhole, its possible origin, and location was completed by Neal (Neal, 1994). The precise date of its formation is unknown although Neal has been able to estimate it roughly in the fall of 1990, or early spring of 1991.

### **2.1.2 Similarity to Other Sinkholes**

One reason for SPR concern with the sinkhole is the similarity to other sinkholes witnessed by mine operators in salt mines. In one other domal salt mine, the operator has confided that their experience has been to see water entry in the **downhole** workings precede sinkhole formation by about a year. Such water entry was typically grouted without fanfare, and emergence of a sinkhole at a later date simply noted. It might be noted that the appearances on the surface of other such sinkholes do not resemble the Weeks Island sinkhole. More typical of other sinkholes viewed has been gradually sloping depressions, usually with standing water. The WI sinkhole surface manifestation is due to the ability of loess to support near vertical walls. Elsewhere there has not always been an

## Weeks Island Sinkhole Volume Changes

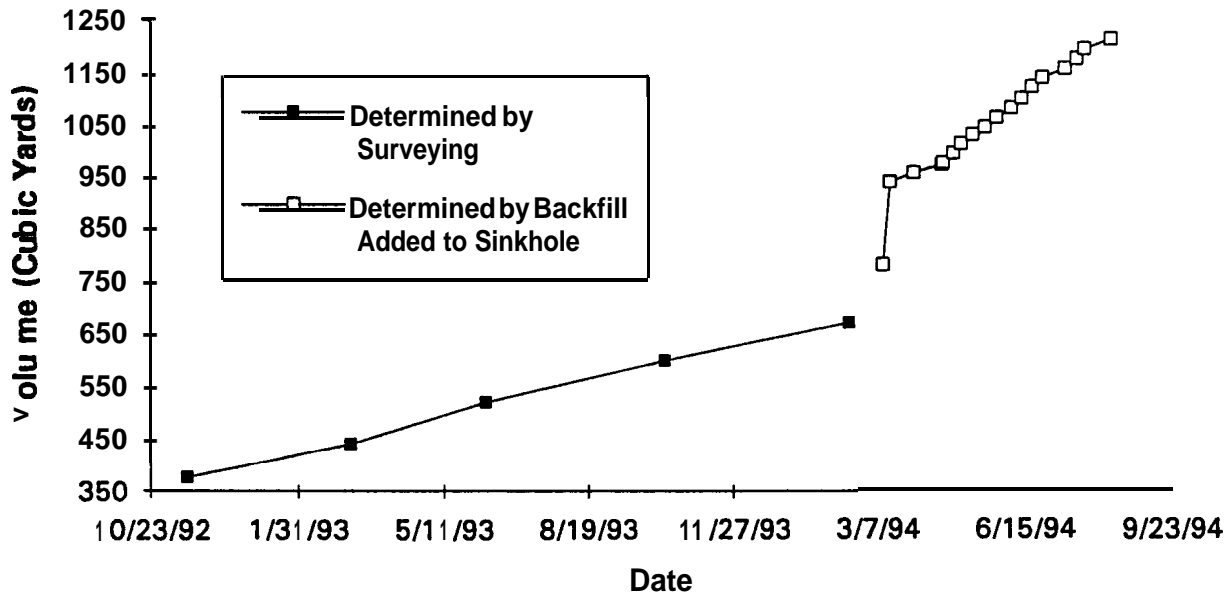


Figure 2. Observed sinkhole volume changes. Note that the method used to estimate the sinkhole volume is different beginning in mid-March, 1994.

exact location match between the mine seepage and the sinkhole location, that is thought to be attributable to the particular mine opening geometry and local salt and soil conditions. There does appear to be consistency in the general observations that such mining associated sinkholes occur near long time outer boundaries of at least one mine.

Another similarity might be drawn between the sinkhole location and the Wet **Drift** location. The Wet Drift was so named as water was encountered in driving a drift between the existing **manways** above the mine and the planned new Morton International mining area in the dome. The water was encountered in an area roughly 100 **ft** above and slightly out **from** the edge of the historical mined levels. Although it may only be coincidence, it should be noted that no explanation for the water in the Wet Drift area has been **confirmable**, i.e., faulting, significant inhomogeneities, etc.

### 2.1.3 Sinkhole Current Status

The sinkhole was surveyed on five occasions from November 1992 until February 1994. During this time it increased in size from about 380 cubic yards to about 670 cubic yards, with the measured rate of increase being nearly linear with time. **In** March 1994 the sinkhole was filled with sand. Several subsequent sand additions has resulted in over 1100 cubic yards of sand fill to date.

This filling of the sinkhole does not prevent continued development of the sinkhole or the underlying mechanism responsible. With time, the surface expression of the sinkhole will redevelop if **solutioning is** allowed to continue or cannot be controlled. The filling of the sinkhole was done in order to reduce risk to personnel while the seismic and drilling investigations to determine its cause were underway around it, and to simplify continued monitoring of its growth.

## 2.2 MINE DIAGNOSTICS

### 2.2.1 Fillhole Brine Inflow

In March 1987, brine was discovered in the **fillhole** sump while running a **wireline** log in one of the fillholes. This log was the first that had been run in the fillholes since fill began. After an intense investigation in the latter half of 1987, the Project concluded that the brine was a combination of connate water, bottom sediment and water (**BS&W**) from the stored oil, and hydrotest water **from** the St. James pipeline. The determination at that time was that the brine did not indicate a leak into the mine.

From February 1988, following brine removal **from** the sump, through February 1992 the data from a **wireline** suspended interface tool in the fillholes showed a trend of declining or level rate of inflow of brine into the sump. During this time, brine was removed from the sump on two additional occasions. The interface tool was removed in February 1992 in order to install and test the emergency **drawdown** pumps in the fillholes. It was reinstalled in March 1993. Brine was again removed from the sump in May 1993. Since the May removal, the inflow rate has increased in rate from about 15 gallons per hour (gph) to a high of about 127 gph in July 1994. Brine injection and mine pressurization were initiated in late July and early August of 1994, decreasing the inflow rate and resulting in a current leak rate of slightly over 100 gph.

### 2.2.2 Mine Pressurization

Since the mine was tilled in 1983, the pressurization rates in the accessible **gas**-filled spaces under the bulkheads and at the vent hole have been monitored. The observed pressurization rates, the original measured volume of the mine, and data from oil movement exercises or opportunities were used to determine the creep closure rate of the mine. The measured volume of the mine used was that derived from the original survey of the mine conducted by Rice and Associates in 1978 during the mine conversion. These data indicated that the overall annual creep closure rate of the mine has been about 160,000 barrels per year (at the normal operating pressure). Geomechanics studies of the expected creep closure concur with this estimate (**Preece**, 1987). This ongoing loss of volume in the mine can be expected to continue at about this rate unless the operating pressure is changed.

Over the years, the mine has been operated with a maximum pressure on the gas under the bulkheads of 7 psig, with minor exceptions. This has required the frequent bleeding of gas from under the bulkheads to maintain the pressure within the prescribed limits. As the gas has been bled and the mine has closed, the oil level in the mine has risen progressively higher. Most recently, in July 1994, additional oil was transferred into the mine in an effort to more completely till the mine and to strap the operating level of the mine to enhance leak detection. Even with this transfer some gas volume still exists in isolated gas pockets throughout the mine, but the volume has been greatly reduced by the transfer. Efforts are currently underway to more accurately estimate the volume of gas from the strapping data. Additionally the mine roof survey data has been contoured which provides **spacial** location and quantity information on the gas pockets within the mine.

### 2.2.3 Identification of Water Entry

Water intrusion into the oil storage levels is ultimately identifiable by monitoring the brine levels in the **fillhole** and Service Shaft sumps and by monitoring the pressurization rate in the mine. The brine in the mine, however, can come from multiple sources, not all of which are leaks from outside. Non-leak sources include **BS&W** from the stored oil, connate seeps in the mine, and water that was in the pipeline from its hydrotests and was pushed into the mine at the initial fill.

The source of the water in the mine can be inferred by chemical and isotopic analysis. The chemical analysis can **differentiate** connate brine from surface and ground waters. The isotopic analysis can also be used to **differentiate** connate and meteoric waters and between different sources of the meteoric water. The source identification of non-connate waters requires that a baseline sample from the possible sources be available for comparison to the assays of the water collected **from** the mine. Analyses to date of the brine from the fillhole, indicate that the brine is a combination of connate and meteoric water, and it is becoming **more meteoric** with time (please see Appendix 14). This trend is interpreted to be the direct result of the continuous inflow of brine from the Weeks Island aquifer fed leak into the mine.

The Service **Shaft** sump has shown no unexplained brine inflow since late 1987. The **fillhole** sump has continued to have brine collecting in it. The rate of inflow generally decreased from 1988 to 1992 but has increased since 1993, notwithstanding the decrease

attributable to oil pressurization in late July 1994. This is covered above in **2.2.1 Fillhole Brine Inflow** and in Appendix 1.

Water entering the mine in the upper level would flow along the floor to the **Service Shaft** or one of about seven raisebores which were drilled between the two levels. Water entering the lower level of the mine might **flow** to either the Service Shaft sump, the **fillhole** sump or an area at the north end of the mine which has a low elevation. The floor of the lower level was reportedly graded to drain towards either the Service Shaft or the **fillhole** sump. Trenches were cut into the floor of the mine nominally to a set elevation although a person present at the time indicates that the trenches were instead cut to a set depth. These trenches were intended to aid in draining oil to the Service Shaft and from the fillholes, and they would allow brine to flow in either location. The trenches could have become blocked by a salt fall, collapse, or one of the numerous salt piles left in the mine. Such a blockage would negate the intent of the trenches to some extent and allow drainage to follow the floor contours which indicate a divide between the fillholes and the Service Shaft. The continued inflow of brine, from the current sinkhole associated leak, into the **fillhole** sump and not to the Service Shaft, indicates that current water/brine entering the lower level preferentially flows to the **fillhole** sump. Thus brine monitoring in the **fillhole** sump is currently probably a better indicator of leakage into the mine than monitoring of the Service Shaft sump.

The pressurization rate of the mine is mainly **affected** by creep closure. There is a negligible **affect** from thermal warming of the oil which is decreasing with time as the oil approaches the in-situ temperature of the salt. (The thermal effect on oil was never large at Weeks Island due to the cool, approximately **80°F**, ambient temperature of the salt surrounding the storage chamber.) The inflow of water into the mine at its currently concluded rate of somewhat over 100 gph is marginally detectable via current mine pressurization data. If the mine is assumed to be closing at about 160,000 barrels per year, the mine volume is changing by approximately 750 gallons per hour. If it is assumed that data uncertainty is at least **10%**, then brine inflows of less than 75 gallons per hour could not be identified by changes in the volume loss rate alone. This subject is discussed more **fully** in 2.2.2 Mine Pressurization, above.

#### **2.2.4 Other Possible Indicators of Water Entry**

During the very early stages of investigation of the sinkhole, it had been suggested that inflow may be detected by monitoring changes in ground water piezometric head around the sinkhole. This suggestion was investigated by the SPR in two studies in 1993. The first study implied that it may be possible to monitor inflow into the oil storage chamber using a system of piezometers (**McHenry**, 1993). A second study which assumed implied permeabilities from the earlier Acres work in the low **Darcy** range implied that monitoring inflow into the oil storage was not possible (Ehgartner, 1993).

During the recent seismic and diagnostic drilling investigation, information was obtained that indicated directly that the water table was depressed in the sinkhole area. If confirmed, this provides a future technique for detection of incipient sinkholes or monitoring existing sinkholes. A part of the follow on diagnostic program includes piezometer installation in areas near the sinkhole and areas remote from the sinkhole.

## 2.3 POSSIBLE SCENARIOS

### 2.3.1 Model Development

In late summer of 1993 Ehgartner at SNL completed simulations of mine development at Weeks Island that showed tensile stresses sufficient to crack salt would have developed over the mine edges in the 1970 time frame (Ehgartner, 1993) (see Figures 7-11). At the end of that decade, some **10** years later, leaks were encountered during the **driveage** of the “Wet Drift,” at a location coincident with the high stress regions in the Ehgartner report. This occurrence is noted and may be significant because there was never general agreement on the specific cause of the Wet Drift leaks. However, that route was abandoned and an alternate approach to the interim **Markel** Mine was established. Ehgartner’s calculations represent recent understanding of salt and have validity because of their background development over a number of years, and also because the resulting subsidence predictions correlate very well with measured survey data. Rather than showing previous factors of three variance between predictions and measured values, the new subsidence predictions easily fall within the range of actual values. More detailed 3-D finite element analyses by **Hoffman** (Hoffman 1994) confirm the prediction of a tensile zone near the top of salt over the mine boundaries when the upper and lower level boundaries are vertically aligned. At Weeks Island this occurs on the South and West boundaries. This vertical alignment condition results in more abrupt flexure as the salt creeps, and thus the tensile zone. Additionally, a dilatant zone which grows with time is predicted to form in the salt. As noted above, the sinkhole and **Wet Drift** both formed over vertically aligned boundaries of the mine within time frames predicted. A conceptual diagram of possible crack development is shown in Figure 3. The deepening with time of a single crack is shown in the vicinity of the mine edge. A single crack is depicted because once the stress field is disrupted, there is no reason for other cracks to form. The drilling program was successful in locating one major crevasse at a depth 72 feet below the top of salt, probably a crack enlarged by dissolution. The crosswell seismic work identified a major low velocity region within the salt and extending downward. Whether there actually only a single dissolution feature or multiple features has not been ascertained. The known dissolution feature is sand or sediment filled thus, as modeling indicates, limiting the flow through the solutioned volume. Ehgartner did model solutioning within an **open** crack in salt, in a hydrologic regime similar to Weeks Island. This work concluded that a leak through an open crack in salt which does not fill with granular material goes uncontrolled within days.

Russo (Russo, 1994, Appendix 2) **further** modeled the situation whereby the crack (modeled as an equivalent round hole) continually fills with overburden material with a definable permeability. The flow and further salt dissolution are subsequently reduced, and the leak continues to enlarge for many years before becoming uncontrollable. Most important **from** this work is the confirmation that water inflow into the mine, through a crack(s) caused by the overall mine closure, has probably been occurring for a significant period of **time** (3 to 10 years) albeit at very low levels. (Although not directly confirmable, this is directly supported by the **fillhole** brine discovery and long term inflow.)



Russo's model predicts that any current inflow would increase 10 fold within five years. If the volume of the sinkhole were assumed to be an indication of the total volume of salt dissolved within the crack at this point in time, the average equivalent radius of the crack as modeled is now somewhat under two feet at a current inflow in the 120 gph range.

## 2.4 CURRENT DIAGNOSTIC ACTIONS

### 2.4.1 Geologic Characterization

Geologic characterization during the diagnostic work at Weeks island consisted primarily of coring, core description and geologic interpretations of data. Six boreholes (Figure 4) were drilled for multiple purposes: (1) to establish geotechnical understanding of the area around the sinkhole and identify the reflecting horizon noted on the seismic reflection profiles; (2) to establish the crosswell configuration wherein seismic tomography could image the sinkhole; (3) to establish locations for hydrocarbon vapor sensing and/or tracer dye introduction, and (4) direct observations of sinkhole geometry and material properties, such as **fracturing** in salt. Core descriptions made on site are contained in Appendix 3.

BH6 was drilled first and continuous core was sought to establish the normal sedimentary section at the sinkhole. The core obtained in BH6 was generally continuous, but overall recovery was incomplete, amounting to about 25 % of the total section down to 175 ft. At that depth the drill pipe stuck and no additional material was obtained until **washover** operations freed the pipe and coring reconvened (Appendix 3). Samples taken in subsequent boreholes were extracted **from** the fluid returns by bucket settling, thus some fine material was probably washed out of the sample.

The sedimentary sections on top of salt are predominantly ancestral Mississippi River sands of medium (~ 1 mm) grain size, and relatively low content of fine material. Occasional gravel **fragments** or lknese were noted, but none were more than a few inches thick or laterally consistent, suggesting they are flood deposits. **Limonitic** stains outlined faint bedding planes in BH6, but other distinctive features or sedimentary structures were not noted, until approaching the sediment/salt transition. The sediment/salt boundary **was** characterized by a zone of black wood fragments up to several feet thick. The **fragments** were sufficiently dense (presumably brine saturated) that they readily sank in water. This wood is thought to be of Wisconsinan age, probably representing back swamp forest along the ancestral river environment

The top of salt was at or very nearly at -104 **ft** msl in five of the six boreholes; all five intersections were within 100 **ft** **from** the center of the sinkhole. The drilled depth to top of salt corresponded **almost** exactly with that interpolated from Acres (1987), i. e., 185 **ft** below the surface. No evidence of fracturing was noted in any of the holes, but the salt was uniformly **soft**, wet, and rather crumbly. High angle banding or other essentially vertical structure in the salt was not noted. Of the five holes that were cored, only BH3 provided reasonably competent salt and good core quality, even though it was also **soft**. BH5 core was entirely **disaggregated**, and BH4 and BH6 showed substantial diskings and broken core. **BH7a** core was smaller in diameter, and although had 100% recovery, was sufficiently **soft** that it could not be handled without breaking. Salt was generally

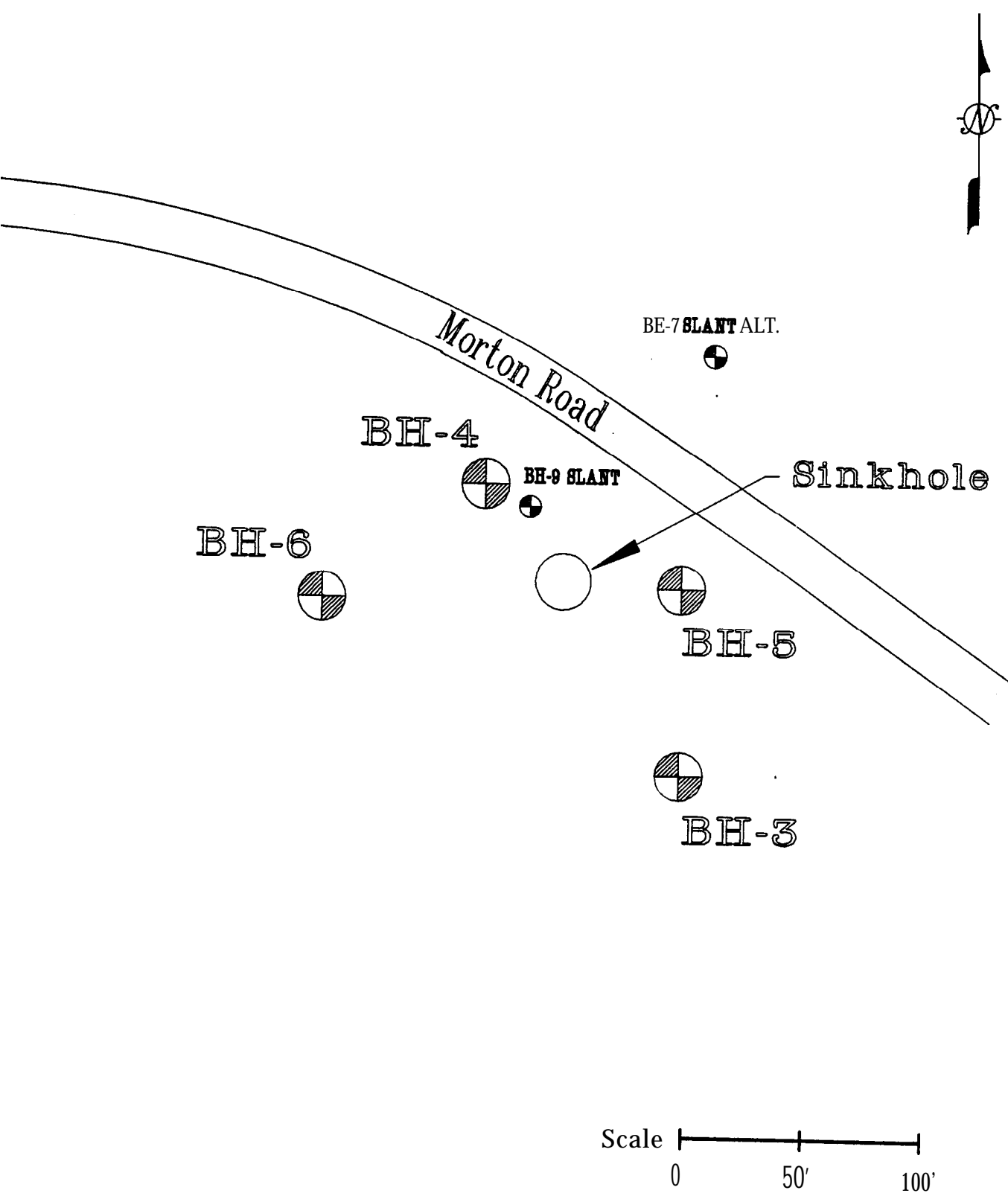


Figure 4. Map showing relative location of Weeks Island sinkhole and boreholes drilled.

RGK:SJB

uniformly granular, with crystal size about 1 - 1.5 cm. Salt was usually very wet and this probably resulted **from** the saturated brine drilling fluid.

Boreholes **BH3, 4, 5, & 6** were constructed primarily for the purpose of providing a test bed for crosswell tomography, but they also provided salt core and top of salt information described above. They also outlined in general the sinkhole geometry by narrowing its **areal** extent within the boreholes, and they provided limited data on static water levels. They may still be used for hydrologic observations, or for additional geophysics.

Angled **borehole BH9** encountered disturbed sand at depths below the elevation of the top of salt in the other boreholes. This sand was judged to be Prairie formation, and not the sand used as sinkhole fill (Appendix 4). As this point at depth was only 8 **ft** from the sinkhole center, it is likely that the hole bottomed in the dissolution feature. Angled **borehole BH7a** entered salt outside the dissolution zone and penetrated salt for another 60 feet vertically. At 250 vertical feet, or -161 **ft** msl, the drill bit entered an apparent **sand-**filled dissolution crevasse. The drill bit eventually extended another 16 feet (angled), taking it 4.5 feet from the sinkhole center. The opposite side of the crevasse was not reached. The sand encountered in this crevasse, at least 72 **ft** below the top of the salt, was similar to sand recovered **from** **BH6**. This saturated-sand environment provided the opportunity for installation of the Sandia in situ hydrological flowmeter (Appendix 9).

The geological evidence suggests the sinkhole structure is quite vertical, based on surface features, the continued strong downward motion of fill sand and the surface monitoring pipe, and the essentially vertical continuity observed in **BH7a**. This vertical structure may continue on downward for substantial depth. However, the geometry below -175 ft is unknown and must be surmised to some extent, based on calculations and hydrological evidence.

#### 2.4.2 Surface Geophysics

Historically, high-resolution seismic reflection surveys at shallow depths (<1000 feet) over salt bodies have been accomplished at numerous locations. They have met with mixed results, presumably because of the continuity and velocity contrast of principal subsurface reflectors (Neal et al., 1993).

Miller (Miller et al., 1993) conducted shallow reflection surveys of a salt dissolution well field near Hutchinson, KS, and was able to image collapse features at depths of 200 to 250 feet, similar in geometry to the potential voids at Weeks Island. Using similar methods, Miller and Steeples from the Kansas Geological Survey acquired similar data at Weeks Island in March 1994.

This seismic reflection survey was designed to detect and delineate geologic or hydrologic features associated with the Weeks Island sinkhole. The details of this study are contained in Appendix 5 and are summarized here. Some 6000 linear feet of seismic reflection data were gathered along 4 profile **lines**, each approximately 1500 feet in length and centered in the sinkhole area. Geophones and seismic cables were placed along these lines to record reflected seismic signals from the seismic source. The reflected energy was recorded, processed, **and** used to construct profiles showing the nature of subsurface materials. The field recording parameters and quality control were based on the reflection interpreted during **walkaway** tests to be from a reflector about 150 **ft** deep. This coherent

reflection event interpretable on all four lines is altered on the east/west line in the proximity of the sinkhole. An offset in the prominent reflection interpretable on all four lines traces a southwest/northeast trend across the study area.

The disturbed reflection on the east/west line, presumed associated with the sinkhole, structurally resembles a chimney type feature or may be associated with the water table.

### 2.4.3 Borehole Seismic Survey

Crosswell seismic tomography is similar in some respects to medical tomography, except that in the latter x-rays are used to construct computer-derived images of internal organs and structures. Seismic tomography depends on sonic and impulse sources, and on the ability to access the subject of interest through boreholes. The construction of images is accomplished through the processing of the seismic velocity data obtained through the region of interest, i. e., between the boreholes. The determination of discontinuities between source and geophone result in seismic images that may show dissolution and/or karst structure in the salt.

In June 1994, on a radius surrounding the sinkhole, four steel-cased holes (6" I.D. minimum casing is required for the seismic tools) were constructed to obtain seismic images across the subsurface geometry of the sinkhole (Figure 4, showing location of holes and drillpads relative to the sinkhole). The cased holes were used for locating a seismic source (an **airgun** or non-explosive impulse device) and recording geophones in opposite holes, respectively.

The primary purpose of the **borehole** seismic survey (For detail please see Appendix 6.) was to provide seismic images of dissolution features in the salt beneath the sinkhole area. Important secondary goals were to identify the seismic reflector imaged at the site by the Kansas Geological Survey earlier this year (Appendix 5), and to image water table drawdown, and any other features related to subsurface collapse and/or anomalous fluid flow related to the sinkhole.

Seismic data acquisition at the site was designed to provide the raw data for crosswell seismic tomograms, vertical seismic profiles (VSP), and crosswell reflection images. At this time, two preliminary crosswell seismic velocity tomograms of the salt and a preliminary single-well vertical seismic profile have been processed. The data acquisition and processing procedures used in generating the tomography and VSP images are described briefly below.

**Crosswell tomography:** The raw data for crosswell seismic velocity tomography consists of the observed travel times of seismic waves which propagate from multiple energy source positions in one **borehole** to multiple receiver positions in another borehole. Crosswell seismic data were recorded in two **borehole** pairs at the sinkhole site, BH4 to BH3, and **BH5** to BH6 (**Figure 1**, Appendix 6). The imaging planes between these **borehole** pairs are roughly perpendicular to each other, and intersect at the center of the \*sinkhole. During the crosswell survey at the sinkhole site, source and receiver depths ranged from 5 to 230 feet.

In crosswell seismic tomography **processing** the planar area between the two boreholes is divided into polygons called "pixels", and the seismic P wave velocity in each

pixel is computed **from** the first arrival travel time observations by a tomographic imaging algorithm. The 2-D display of seismic velocities within the pixels is called a “tomogram”. Travel time picking and tomogram processing was performed on site, as the crosswell data were acquired.

The P wave velocity in saturated undisturbed soil at the site is approximately 6,100 feet/second, while salt velocity ranges **from** 12,000 to 14,000 feet/second. It is expected that salt dissolution “cavities” **filled** with disturbed saturated soil would cause observable low velocity anomalies in the crosswell seismic tomograms. Figures 2 and 3 (Appendix 6) are the preliminary P wave velocity tomograms for the **borehole** pairs **BH3** and **BH4**, and **BH5** and **BH6**, respectively. These tomograms show only the depth range from 170 to 230 feet below ground surface, and were processed to emphasize imaging within the salt. Source depths **from** ground surface to 230 feet, and receiver depths from 90 to 230 feet were used in generating these images. Seismic velocities are color coded with the highest velocities in red and yellow and the lowest velocities in blue and green.

Both tomograms clearly display substantial low velocity features which presumably are due to salt dissolution. The shallowest low velocity anomaly in the **BH5/BH6** tomogram intersects the top of the salt more or less directly beneath the sinkhole. In the **BH3/BH4** tomogram the shallowest velocity anomaly is centered about 17 feet south of the sinkhole centerline (toward **BH3**). The low velocity features on both tomograms trend southward with increasing depth, and show a generally irregular or complex spatial distribution. Drawing a quantitative relationship between tomogram velocity and the boundaries of the salt dissolution surface is difficult at present since a continuum of velocities from about 9,000 **ft/sec** to 12,000 **ft/sec** is present in the tomograms. In general the vertical resolution of velocity tomography is superior to the lateral resolution. One approach to using the tomography images to guide placement of grout injection wells would be to drill the center of the anomaly first, to **verify** the existence and vertical extent of the dissolution cavities. By placing subsequent wells toward the edges of the anomaly, until the edge of dissolution is detected, the correspondence between seismic velocity and the lateral extent of the dissolution cavity can be established.

The reduction of crosswell seismic tomography data (Appendix 6) is still in progress, however the following preliminary results have been obtained: (1) there is a lower-velocity zone below the sinkhole which implies the presence of a sediment filled dissolution feature, and (2) evidence of the implied water table deflection below the sinkhole observed in the surface seismic and well measurements is substantiated.

**Vertical Seismic Profile (VSP):** Raw data for a VSP were acquired in **borehole BH5** by using a 20 cubic inch **airgun** deployed at the surface as the seismic energy source (Figure 4, Appendix 6). This seismic source provided ample energy for observing first arrival and reflected events. Shot records were taken with the **borehole** receivers placed at 2.5 vertical intervals from 5 to 230 feet below ground surface. With this recording geometry it was possible to construct a time-depth table (Figure 5, Appendix 6) which shows the vertical seismic (one-way) travel time **from** ground surface for each receiver depth. This information is useful for converting surface reflection two-way times to depth.

After wavefield separation and filtering of the VSP image (Figure 6, Appendix 6), two up going reflected events are clearly visible. The depths of the two reflecting

### 2.4.7 Surface Self Potential Survey

The primary purpose of the self potential (SP) survey was to establish whether this technique could provide a rapid and relatively inexpensive means of locating water table **drawdown features** related to sinkhole development. This technique is the only geophysical surveying method in which the signal response is derived primarily **from** groundwater movement. In this application, SP surveying is based on the streaming potential effect, in which a DC electric field is established by fluid flow through permeable soil and rock.

Based on details provided in Appendix 11, the following observations are warranted:

- (1) SP data quality were generally good over the roughly 9,000 feet of data acquired. Although significant cultural noise was present within the surveyed area, standard potential field data analysis techniques were sufficient to separate signal **from** the noise.
- (2) The data analysis indicates significant streaming potentials (100 **mV** peak-to-peak) in the area of the sinkhole and the two seismic anomalies north of Morton Road.
- (3) Matching synthetic data with the observed SP field indicates that the anomalous streaming potentials are likely to result **from** vertical fluid flow along a set of vertical or near-vertical planar surfaces, probably shear zones or faults,
- (4) At the sinkhole site, the depth to the field source is very shallow (about **5** feet), indicating probable vadose zone flow. North of Morton Road, close to the seismic anomalies, the top of the field source appears to coincide roughly with the water table depth (90 feet).

These findings are consistent with the results obtained from surface seismic and other geotechnical data.

### 2.4.8 Stable Isotope Constraints on the Origin of Brine

There is a small amount of the heavier stable isotope of oxygen (**<sup>18</sup>O**) and hydrogen (**D**, deuterium) in all natural waters. The amounts of these isotopes in water samples are highly variable and depend upon the source and history of the water. In effect, the stable isotopes can often be used as natural tracers to understand the source(s) of mine leaks, aquifer contamination, and other problems involving surface-ground water interactions.

The brine in the fill holes has been studied for isotopic amounts since 1987. The results of this study are detailed in Appendix 14 and are summarized here. From 1987 to 1990 the data evolved steadily toward more **<sup>18</sup>O**- and **D**- depleted values. From 1992 to 1993, the data became more D-rich as **<sup>18</sup>O** continued to decrease. The current trajectory is directly toward the values of the overlying aquifer (as sampled in the well over the fill-holes and Morton Salt Co Well #7). The data provide evidence implying that external water has been leaking into the facility since at least March, 1992.

east of the sinkhole; these two observed high-gas regions may be indicative of the subsurface anomalous Shear Zone E. Along discontinuous segments of Transects F and F', north of Morton Rd., somewhat east of the sinkhole; data observations provide a weak correlation with observed seismic lows in the vicinity. Just north of the fill hole area; and, **directly** above the buried SPR pipeline. Correlation of any of the high gas zones directly with the sinkhole is **difficult**. The high gas zones do apparently correspond well to one or more of the notable seismic features and/or surface indications of subsurface geologic anomalies.

The gas mapping survey did not find a direct. gas-release pathway from the SPR oil to the immediate vicinity of, or in, the sinkhole. Our original assumptions that the sinkhole was functioning as a direct chimney vent to **funnel** gases to the surface through a presumed fracture network and could be detected by means of gas mapping, has not proven to be conclusive with the *available* gas data. It is possible that other factors occurring at the Weeks Island site, e.g., downward and lateral flow of groundwater in the sinkhole vicinity may have perturbed gas seepage patterns enough to mask a conclusive result. Further sampling in concentric patterns about the immediate sinkhole in the vicinity might resolve the uncertainties.

Observed patterns of the gas seeps, in conjunction with or in comparison to the geophysical diagnostic work at Weeks Island and results, suggest -- but not definitively -- a structural control associated with fracture development processes. Fracture permeability may be associated within and near any of the mapped geologic anomalous zones. It is possible that the patterns generated by the gas mapping survey data are surrogates of the overburden fracture pattern(s) produced by stresses that created the sinkhole.

Further substantiation of the above interpretations and conclusions could potentially be obtained by a somewhat expanded near-surface gas mapping program -- particularly by using the enhanced analytical equipment and techniques implemented near the end of the current survey.

The opportunity to obtain down hole brine and gas samples from the bottom of the slant hole in salt, in the vicinity of the sinkhole, did not present itself. These samples could not be obtained due to the early injection of dye into the bottom of the slant hole.

Based on the evaluations, it is not planned to proceed with gas analyses from drilling returns, nor **downhole** positive pressure gas permeability tests. Planned laboratory tests on salt cores obtained will probably provide more benefit to the SPR Project.

#### **2.4.5 Downhole Flow Measurements**

An In Situ Permeable Flow Sensor was emplaced into **borehole BH7a** to measure the direction and magnitude of the groundwater flow velocity in the throat of the sinkhole. The details of this study are contained in Appendix 9 and are summarized here. The goal of this effort was to help distinguish between two competing hypotheses regarding the significance of the sinkhole. One hypothesis is that the sinkhole is part of a fissure or topographic canyon in the top of the salt which is carrying water horizontally off the top of the dome. The other possibility is that there exists a hydrologic connection between fresh water above the salt and the petroleum reserve. Measurements of groundwater flow directly in the conduit, below the top of the salt, can help to resolve this issue. If predominantly horizontal flow is observed then flow of water off the salt dome is probable

whereas if predominantly downwardly directed flow is detected then flow into the reserve is likely.

In Situ Permeable Flow Sensors are new, Sandia-developed instruments which use a thermal perturbation technique to directly measure the magnitude and direction of the full three dimensional groundwater flow velocity vector characteristic of an approximately  $1\text{ m}^3$  volume of the subsurface (Ballard et al., 1994).

The basic principle of operation is to bury a long thin heated cylinder with an array of surface mounted temperature sensors in direct contact with the formation at the point where the flow velocity measurement is to be made. The heat emanating from the probe warms the ground and the water surrounding the instrument. In the absence of any flow past the device, the temperature distribution on the surface of the cylinder will be independent of azimuthal position on the probe and symmetric about the vertical midpoint on the probe. The ends of the probe will be cooler than the vertical midpoint because heat transfer away from the ends of a finite length heated cylinder is more efficient than from the midsection. If there is flow past the device then the heat emanating from the surface of the probe will be advected around the device by the flowing water with the result that the probe will be somewhat cooler overall than when there is no flow and the upstream side of the probe will be cooler than the downstream side.

Figure 2 (Appendix 9) shows the temperatures measured by the 30 temperature sensors on the surface of the probe as a function of time. Before activation of the heater, the temperature of the subsurface was approximately  $23\text{ }^{\circ}\text{C}$ . When the heater was activated, the temperature of the surface of the probe increased dramatically with the temperature at some locations increasing much more than at other locations. After a day, the temperature of the probe continued to increase even though the power output of the heater remained constant. In addition, the spread of temperatures decreased with time. Figure 3 (Appendix 9) illustrates the vertical temperature distribution on the surface of the probe as a function of time. Each curve in Figure 3 (Appendix 9) shows the temperature distribution on a different day. The most important feature to note is that throughout the time that measurements were made, the top of the probe was relatively cool and the bottom of the probe relatively warm, indicating that the heat emanating from the probe was being advected downward by groundwater flowing vertically downward past the probe. A small component of flow oriented in a direction perpendicular to the long axis of the probe was also observed but is consistent with the fact that probe was not oriented vertically in the ground. The temperature distribution is unambiguous: large, downwardly directed flow with insignificant horizontal flow was observed. The fact that the probe increased in temperature and the vertical temperature distribution became more symmetric with time indicates that the downward flow velocity decreased in magnitude significantly during the course of the measurement period.

Figure 4 (Appendix 9) illustrates the magnitude of the downwardly directed flow velocity as a function of time. At first the magnitude of the flow was around 4 feet/day. The flow decreased rapidly at first but appeared to be leveling off at about 0.5 to 1.0 **ft/day** by the end of the data collection period. The permeability around the probe decreased during the two week measurement period due to the dynamic nature of the fluid conditions or possibly the disturbed nature of the sand in the vicinity of the sand in the conduit. Please see Appendix 9 for a detailed discussion.

Another observation is that the flow sensor was apparently being carried **downhole** by sand flowing downward in the conduit. As previously mentioned, the probe was connected to the surface by 1 inch diameter PVC pipe. Figure 5 (Appendix 9) shows the downward displacement of the top of this pipe as a function of time. The data indicate that the pipe was being carried into the hole at a rate of 1 inch/day. A second flow sensor, which was emplaced in **borehole BH9** at a depth of approximately 180 feet below the sinkhole, is also being carried **downhole** at a rate of 1 inch/day. At the time of this writing, no groundwater flow velocity data has yet been obtained from this probe. There is also a pipe which was inserted **directly** into the sinkhole at the ground surface and the bottom of which is now at a depth of approximately 85 feet. The pipe is also moving downward at about 1 inch/day (Dick Berry, pers. **comm.**). Altogether there are three observation points at depths of 85, 180 and 250 below ground surface where downward flow of sand of about 1 inch/day has been observed.

The downward groundwater flow observed in **BH7a** strongly suggests that groundwater is leaking into the oil repository. The alternative explanation, that the sinkhole is connected to a channel in the top of salt where water is flow off the dome would seem to require horizontal flow; only vertical flow was observed.

The observation that sand is flowing downward at a similar rate at depths of 85, 180 and 250 below the surface suggests that the cross sectional area of the conduit is reasonably constant down to at least 250 feet depth.

#### 2.4.6 Dye Injection

Rembco Engineering Corporation, under contract to **DynMcDermott** Petroleum Operations Company, injected dyed tracer dye into boreholes **BH7a** and **BH9** during June and July 1994. The dye injection was performed to establish irrefutable proof of a hydrologic connection between the oil storage chamber and the overlying aquifer.

The basic procedure for injection of dye into the sinkhole dissolution zone was to mix a **10%** concentration of Rhodamine **WT** in saturated brine on the surface. This concentration is the highest concentration achievable. The dye was then pumped down the borehole, **using** a tremie tube, while monitoring the brine level in the well casing to ensure that injection pressures are kept low. Actual procedures used are in Appendix 10.

Attempts at injecting dye into the bore of **borehole BH9** resulted in a backflow of brine in the **annulus** of the well casing. The tremie tube was jetted into the formation to improve dye intake. A total of 2,000 gallons of dye saturated brine were injected at 5 gpm using this procedure. Samples of brine are being taken from the fill hole sump on a daily basis for analysis for Rhodamine WT.

No tracer dye has yet been identified in the fill hole sump to this date. It is **difficult** to estimate transit time for water/dye once it enters the mine given the many potentially tortuous paths that are possible.

The possibility that the dye has a preference for dispersion in oil has been examined and is apparently not a factor. Oil sampling could be started but the lack of oil circulation in the mine may result in a very long time until **diffusion** places a detectable amount of dye under the service shaft.

#### 2.4.7 Surface Self Potential Survey

The primary purpose of the self potential (SP) survey was to establish whether this technique could provide a rapid and relatively inexpensive means of locating water table **drawdown** features related to sinkhole development. This technique is the only geophysical surveying method in which the signal response is derived primarily from groundwater movement. In this application, **SP** surveying is based on the streaming potential effect, in which a DC electric field is established by fluid flow through permeable soil and rock.

Based on details provided in **Appendix 11**, the following observations are warranted:

- (1) SP data quality were generally good over the roughly 9,000 feet of data acquired. Although significant cultural noise was present within the surveyed area, standard potential field data analysis techniques were sufficient to separate signal from the noise.
- (2) The data analysis indicates significant streaming potentials (**100 mV** peak-to-peak) in the area of the sinkhole and the two seismic anomalies north of Morton Road.
- (3) Matching synthetic data with the observed SP field indicates that the anomalous streaming potentials are likely to result from vertical fluid flow along a set of vertical or near-vertical planar surfaces, probably shear zones or faults.
- (4) At the sinkhole site, the depth to the field source is very shallow (about **5** feet), indicating probable vadose zone flow. North of Morton Road, close to the seismic anomalies, the top of the field source appears to coincide roughly with the water table depth (90 feet).

These findings are consistent with the results obtained from surface seismic and other geotechnical data.

#### 2.4.8 Stable Isotope Constraints on the Origin of Brine

There is a small amount of the heavier stable isotope of oxygen (**<sup>18</sup>O**) and hydrogen (**D**, deuterium) in all natural waters. The amounts of these isotopes in water samples are highly variable and depend upon the source and history of the water. In effect, the stable isotopes can often be used as natural tracers to understand the source(s) of mine leaks, aquifer contamination, and other problems involving surface-ground water interactions.

The brine in the fill holes has been studied for isotopic amounts since 1987. The results of this study are detailed in Appendix 14 and are summarized here. From 1987 to 1990 the data evolved steadily toward more **<sup>18</sup>O**- and **D**- depleted values. From 1992 to 1993, the data became more D-rich as **<sup>18</sup>O** continued to decrease. The current trajectory is directly toward the values of the overlying aquifer (as sampled in the well over the fill-holes and Morton Salt Co Well #7). The data provide evidence implying that external water has been leaking into the facility since at least March, 1992.

#### 2.4.9 Brine Injection and Sinkhole Monitoring

In March of 1994 a monument was established in the sinkhole. The elevation and positioning of that monument and subsequent additions to it have been monitored continuously since. Also in March, the sinkhole was filled with sand, and has been continuously refilled on an as needed basis. Beginning in August of 1994, saturated brine has been introduced into the crevasse below the **sinkhole** through the bottom of **BH7a** at rates of 2-3 gpm. There was a coincidence between introduction of brine and cessation of the need to backfill the sinkhole (and downward displacement of the monument). This indicates a possible cause and effect relationship. The introduction of brine into the crevasse has decreased the potential for leaching of salt leading into the mine. Presumably it is the leaching and removal of salt which is being **infilled** by sediment, and subsequently replaced at the surface as backfill. A **tabulation** of the results of the monitoring, **backfilling**, and brine injection are contained in Appendix 15.

### 2.5 ADDITIONAL DIAGNOSTIC ACTIONS

#### 2.5.1 Inspection for Other Sinkholes

In December, 1993, Sandia and **DynMcDermott** personnel scouted a portion of the surface overlying the perimeter of the mine. During this inspection, no additional sinkholes were discovered. A more detailed survey of the entire perimeter of the mine may be required. Such an inspection would have the purpose of determining the existence of other sinkholes to be identified as possible targets for future grouting and for partial verification of the modeling which indicates that sinkhole formation is likely over the mine perimeter. The inspections should be made on some routine basis in the future to determine if new sinkholes are developing.

A major problem with surface inspection for sinkholes is maintaining orientation of the search crews through the thick underbrush. This problem will overcome shortly by establishing monuments over the corners of the mine and intervals along the perimeter. Clearing of the thick underbrush may be eventually accomplished. Use of a portable LORAN system could also provide better orientation for personnel making the surface inspection. Current systems provide positioning within about 25 to 50 feet if properly initiated.

#### 2.5.2 Markel Mine Inspection

The original Weeks Island Risk Assessment Study (**Beasley** et al., 1985) identified the Markel Mine as posing a major risk which could jeopardize oil storage and withdrawal. The study recommended monthly inspection of the Markel Mine as well as a dimensional survey of the structure.

The recommendations of the risk assessment study were later followed by Risk Abatement Committee recommendations to build isolation bulkheads in the Johnston and Sandrik Drifts which included access doors for Mine inspection. It was further agreed that inspection of the Markel Mine should be performed quarterly.

The isolation bulkheads have been completed for more than a year with the isolation doors still open. The doors need to be closed to assure complete mitigation of the risk associated with the Markel Mine serving as a large reservoir for water that may flood the DOE facility as a result of a **shaft** failure. A standing recommendation to close the doors by the Risk Abatement Committee currently exists.

Inspection of the Markel Mine was suspended in 1989 due to safety concerns. These safety concerns were a topic of discussion until October 1992 when the mine safety was assessed by the Mine Safety and Health Administration (**MSHA**). MSHA found that the mine, as is, was unsafe for human access and concluded their inspection by questioning the **stability** of the mine structure. No further inspections of the Markel Mine were made pending a decision to perform maintenance of the mine.

The risk associated with the Markel Mine has recently become an issue as a result of the MSHA concerns on the mine stability. Continuing studies by the SPR indicate that the probability of pillar failure in the Markel may be higher than assessed earlier, and that such failure may result in inflow into the Markel mine. The studies **identify** that there is risk to the Morton Mine due to the proximity of the Morton Production Shaft to the Markel Mine.

In conclusion, the Markel Mine poses a real risk to the Morton Mine and, to some extent, to the DOE Oil Storage. Based upon this risk, inspections and the necessary maintenance to accomplish such inspections on a quarterly basis, need to be initiated. Additionally, some action is necessary to develop a grouting plan for the Markel Mine and to insure that equipment capable of drilling and grouting in the Markel Mine is available.

### 3. PREVENTATIVE AND MITIGATIVE OPTIONS

#### 3.1 MINE PRESSURIZATION

With the development of a sinkhole and diagnosed leak, increasing the pressure within the mine to a level somewhat below the hydrostatic pressure will reduce or delay the possibility of future leak development, reduce the rate of solutioning of a possible existing leak(s), and minimize the consequences of a leak. Operating the mine at a significantly increased pressure, however, will require a **safety** analysis to ensure that it can be safely operated from personnel and equipment perspectives.

In July 1994, slightly over 800 kbbl of oil were transferred into the mine over a two week period. The reported inflow rate decreased from 127 **bbl/day** to 103 **bbl/day**, confirming the anticipated inflow rate response to mine pressurization. Ostensen has analyzed the anticipated benefits of mine pressurization assuming various crack orientations or geometries. Most important is the conclusion that mine pressures (at the mine roof below the sinkhole) will have to be in excess of 180 psi for oil to escape from the salt. The time dependence of oil movement upward through the leak in the event of mine pressurization has also been analyzed. It is significant that even under a full hydrostatic head pressurization, it requires several months for oil to permeate upward through the sediments filling the leak path before oil could be lost to the environment.

Increased pressure in the storage chamber also improves the ongoing monitoring of integrity of the facility. With increased pressure, the existing inert gas pockets becomes smaller and less compressible, and therefore not as readily mask minor pressure changes that would result **from** small quantities of water leaking into the mine. The effect of the recent oil transfer is still being analyzed as to how much improved is the leak detection and water **inflow** monitoring capability using mine pressure.

The mine could be converted to operate as a pressurized cavern, similar to the way the solution mined caverns are operated if the leak can be plugged. This would require a large volume brine source and brine disposal capability which would be used for any oil withdrawal and refill of the pressurized mine. It might require that the manifold room as it now exists be abandoned. In such case, a new means of controlling flow **from** the mine would be required, such as control valves on the surface.

An alternative, but less desirable, method of achieving some of the benefit of operating the mine at an increased pressure would be to maintain the high pressure only during the **drawdown** readiness mode. The mine would be depressurized either prior to or at the start of oil movements for exercises or drawdown. In order to minimize pressure fluctuations and salt stability problems in the mine, exercises would have to be limited if the mine is to be operated at an elevated pressure. This approach requires minimal new facilities be installed at the site as the present **drawdown** system would continue to be usable as long as a significant leak does not develop. This method does not consider, however, the consequences of a leak part way through a **drawdown** (4.1.4 below).

##### 3.1.1 Effect on Leak Inflow

Consideration of an increase in operating pressure in the mine is driven by a need to minimize (1) the hydraulic pressure difference that would drive brine flow into the mine,

and (2) the lithostatic pressure difference which drives salt creep. Estimates of the capillary pressure within a sand-filled fissure conclude the pressure is too low to prevent oil migration through brine-filled sand (Ostensen, 1994, Appendix 12), therefore, the static pressure head of the oil must be maintained below the top of the salt. This pressure, about 140 psi on the oil at the Service Shaft bulkhead, will prevent oil **from** being driven through the existing or future flow paths into the overburden above the salt, but will reduce the driving pressure of a brine leak from about 230 psi to about 90 psi at the roof of the storage chamber. Additionally, the pressurization will decrease the volume of brine which can leak into the facility by approximately 55,000 barrels. This decrease in available space would result in decreased risk of surface damage and additional dissolution should an uncontrollable inflow occur. Also, the ongoing salt creep will be appreciably reduced thus diminishing the perceived ultimate source of inflow concern (see following discussion).

### 3.1.2 Effect on Long-Term Creep

Reduction of cavern creep has two benefits. One is that with reduced creep, the loss of mine volume, now estimated to be at least 160,000 barrel per year, will decrease. This will help stabilize the storage capacity over the **life** of the mine. The second, and more significant result of decreased creep, is that the tensile stresses imposed on the salt near the top of the dome will be decreased. This will result in a decrease in or slowing of fracture development in the salt and resulting other leak path(s) development into the storage chamber.

Analyses (Hoffman, 1994) show the magnitude and extent of both the tensile and dilatancy (**microfractured**) zones to slightly decrease as the mine is pressurized to oil head at top of salt. Most significant, surface subsidence rates and volumetric creep closure are reduced by approximately an order of magnitude. Pillar stability in the oil storage levels is improved due to the added confining pressure. Prior to pressurization, tensile stresses and dilatant behavior are predicted in the pillars. Some of these effects were noted prior to oil fill by Acres (Acres, 1977) when pillar decay up to 15 **ft** into the pillars was observed. Pressurizing the mine eliminates tensile stressing in the pillars and dilatant behavior, which will extend its life. It will also reduce the stress and deformation characteristics that cause fracture and potential flow paths through the overlying salt.

### 3.1.3 Necessary Mine Changes

In order to safely operate the mine at an increased pressure, several actions must be completed. These actions include:

1. Complete the upgrades of the submersible pump system and **wireline** penetrations to withstand increased pressure in the storage chamber,
2. Upgrade or install hydrocarbon sensors on the Service Shaft bulkhead to detect spills,
3. Consider locking in or blinding all valves on the bulkhead penetrations to minimize spills,
4. Install at least one emergency **drawdown** pump in a **fillhole** to provide a means to depressure the mine should an oil spill occur in the manifold room, and

5. Space the submersible pumps to allow removal of oil from either the bottom or top of the mine, (in process currently) and
6. Provide a source of fluid to maintain pressure during drawdown.

The Risk Abatement Program upgraded the bulkheads in Raisebores 1 and 2 and the Service Shaft and investigated the bulkheads in the Production Shaft and Markel Incline. These studies and upgrades were made only to the bulkheads themselves and not to the submersible pumping system and the various pipes that penetrate the bulkheads. The pumps and penetrations were investigated at a later date to determine if they will withstand the increased pressure that could develop in the storage chamber if a brine leak develops. The result of this investigation is that some upgrades are required. The upgrades which are currently in the process of being completed are:

1. Replacement of the gaskets on the pump casing flanges,
2. Sealing of the submersible pump electric cable penetrations,
3. Installation of **packoffs** around instrumentation cables in the Service Shaft and the fillholes, and
4. Upgrading the pump motor lubrication oil system to ensure that it will always be at a higher pressure than the oil in the mine.

A pump(s) needs to be installed in the fillholes if the mine is pressurized so that the mine can be depressurized in the event oil spills or leaks in the **manway**. If an oil spill occurs, it could not be shut off or cleaned up except by depressurizing the mine to remove the driving force for the oil spill. With an oil leak in the **manway**, operators could not safely enter the manifold room to align the submersible pump manifold to allow their use for depressurizing the mine.

Use of an emergency **drawdown** pump(s) in the fillholes for this purpose would require a change in recovery criteria that require recovery equipment be stored at an **off-site** location. The emergency **drawdown** pumps are designated as recovery pumps for the submersible pumping system.

The possibility of an oil spill occurring in the **manway** can be minimized by isolating the piping in the mine from the bulkhead penetrations. This piping includes the oil withdrawal pipes and the nitrogen venting system. The isolation can be accomplished by either locking the connecting valves in the closed position or physically disconnecting the piping and installing blind flanges.

Early detection of a oil leak can be accomplished by installing hydrocarbon sensors on the bulkheads. These sensors would signal the control room that oil fumes had been detected so that prompt action could be initiated to depressure the mine and minimize the size of the leak. The existing hydrocarbon warning system may be sufficient to provide this capability but verification is needed.

Vertically spacing the pumps in the Service Shaft below the bulkhead is required to allow removal of oil for a conventional **drawdown** due to water leakage, or an emergency **drawdown** due to water leakage into the mine. The specific arrangement of the pumps will need to be determined with consideration of system hydraulics. However, the intent would be to space them in a pattern such that there are some pumps left in the Service

Shaft sump, some pumps are repositioned just below the Service Shaft bulkhead, and possibly some pumps are positioned near the mid-point of the mine. The pumps near the bulkhead would not be used during a conventional **drawdown** while the pumps in the sump would not be used in the event of an uncontrollable water inflow. The pumps near the middle of the mine could be used in either scenario until the oil level reached the suction (or NPSH requirements) of those pumps. In the event of a conventional drawdown, some of the pumps **from** below the bulkhead or at the mid-point could be lowered back to the Service **Shaft** sump to maintain required **drawdown** capabilities.

In order to space the pumps in the Service Shaft, they need to be relocated before any oil pressure increase, either planned or as a result of water inflow. Due to space limitations in the manifold room, it is impractical to develop a system to control the oil and allow movement of the pumps while the storage chamber is pressurized.

### 3.2 GROUTING

It may be possible to stop the water inflow into the mine by grouting from the surface. This technique has been tried at both Weeks Island over the Wet Drift in 1977 and 1978 and at other salt mines in salt domes. Generally, the technique has not been greatly successful, primarily due to the high cost and time involved as compared to grouting from underground. Drilling to intersect and grout off leaks from underground is generally cheaper and quicker, and the visible leak provides a more definitive target for grouting than can be obtained **from** the surface. However, in the case of water leaking into the storage chamber, access **from** underground is not possible; and surface grouting is the only available option.

The difficulties associated with surface grouting involve determining a target zone, and real time diagnostics on its effectiveness. Due to the hydraulics of water flow after it enters the mine, any actual measured **inflow** may not be impacted by a grouting program for a significant period of time. Additionally, a leak from the surface may consist of numerous small channels near the top of salt which funnel, with depth, into one zone. If this major zone is not found, grouting of small feeder channels will only temporarily impede the leak into the mine.

Now that a sand channel to the mine has been inferred, grouting **from** the **surface** may be effective. Any surface grouting program is likely to be expensive and short lived requiring repeated grouting to maintain the seal. Openings that have been temporarily sealed by grouting are likely to be reopened as the salt extension that initiated the fractures continues to occur. A more thorough discussion of surface grouting is given in Appendix 13 and in the **DRAFT** Weeks Island Surface Grouting Plan (**DynMcDermott**, 1994).

### 3.3 ENVIRONMENTAL CONCERNS

An uncontrolled water leak into the oil storage chamber could result eventually in environmental damages from either the loss of oil into the aquifer and possibly onto the surface or into waters overlying the dome or from damage to the ground water and surface that may result from subsidence over the mine.

Currently, water can leak into the storage chamber without oil leaking out of the mine. This water leakage with no oil outflow will, if allowed to continue, fill the mine and pressurize the oil to near hydrostatic pressure. Once the mine pressure is in equilibrium with the ground water hydrostatic pressure (approximately 230 psi in the upper level), oil could simultaneously float up through the leak path that allowed water **to** enter (Section 3.1.1). The presence of overburden materials would greatly retard this exchange. The rate of oil flow will depend upon the size and configuration of the leak path. This oil could eventually contaminate the aquifer, and depending upon characteristics of the overlying sediments and rate of oil leakage, may appear in Weeks Bay and the wetlands around Weeks Island. It is unlikely that oil would actually reach the surface on the Island with this scenario. Once released **from** the storage chamber, oil would be extremely **difficult** to contain or clean up, particularly in the aquifer.

If a leak into the mine were allowed to continue sufficiently that a large conduit or leak was developed, or the supporting mine pillars in the vicinity of the leak become unstable and collapsed due to solutioning, the leakage path into the mine could wash existing sediments or overburden from above the mine or in the flow path into the mine. This could create a much larger surface sinkhole. The size of the sinkhole and immediate further solutioning would be limited by the volume in the mine available for filling. If the velocity of the inflow after it entered the mine was low, the volume available in the mine for filling with overburden material is essentially a cone, or some portion of a cone, approximately 75 feet high (the height of the rooms in the upper level) with an angle of repose approximately equal to that of sand. This cone would be restricted somewhat by the presence of the mine pillars. The velocity of any inflow in the mine will be low provided the mine remains essentially fluid filled. If the mine were only partially fluid filled, overburden materials could be washed or carried away **from** the vicinity of the entry point and the size of the sinkhole formed would be greatly increased.

Depending upon the location, rate and quantity of material movement, surface facilities could be severely damaged. This damage could result either from the sinkhole formation and subsidence occurring adjacent to the surface facilities or due to movement of ground water into the mine which could result in additional subsidence related to the local dewatering. Underground facilities such as the shafts could also be adversely impacted by a rapid movement of ground water towards a sinkhole.

## 4. RESPONSE OPTIONS

### 4.1 OIL WITHDRAWAL

#### 4.1.1 Conventional Drawdown

As long as the current leak or leakage into the mine remains small, normal drawdowns (national emergency or exercises) can be conducted essentially in the present design mode. If the pumps are vertically spaced within the Service **Shaft** as discussed above in Section 3.1.3, the number of pumps available for an extended **drawdown** may be reduced, depending upon the results of the hydraulic study for spacing them. The Service **Shaft** submersible pumps may also be supplemented by pumps installed in the fillholes, if these have been installed as a result of operating the mine at an elevated pressure during periods of **drawdown** readiness.

#### 4.1.2 Geotechnical Emergency - Water Leak Above the Bulkheads

In the event a water leak develops above the oil isolation bulkheads, which would render the manifold room unusable, oil withdrawal could be accomplished using the emergency **drawdown** system placed in the fillholes. This requires no change from present plans.

#### 4.1.3 Geotechnical Emergency - Water Leak into the Storage Chamber

Should the water leak into the storage chamber greatly increase, both the Service Shaft sump and the **fillhole** sump would become flooded with brine. The existing submersible pumps cannot lift the brine to the surface due to discharge head limitations. This would prevent **drawdown** by the existing **drawdown** systems.

In this type of emergency, oil could be removed either by allowing the mine to reach to till hydrostatic pressure and allowing oil to flow out of the vent hole, or by using selected submersible pumps in the Service **Shaft** (if they have been relocated to just below the Service **Shaft** bulkhead). In the event the vent hole was used for oil withdrawal, it would need to be connected to the oil pipeline to St. James. A design and piping for this contingency do not presently exist. This connection could probably be designed so that in the event of an emergency, fabrication could be quickly started. This system would allow oil flow at about 120,000 barrels per day or a rate equal to the rate of water inflow if it is less and no supplemental source of fluid is available for injection into the mine. It is emphasized that this use of the submersible pumps requires that they be previously positioned below the bulkhead. The obtainable rate will depend upon the number of pumps that are moved and the pressure in the mine.

During an emergency **drawdown** due to water leaking into the mine, consideration should be given to controllably injecting water or brine to replace the quantity of oil withdrawn. This would (1) decrease the amount of water leaking into the mine through the leak path (and thus minimize **further** dissolution within the leak path), (2) reduce the **inflow** velocity and possible movement of overburden material washed into the mine, and (3) maximize the rate of oil withdrawal. The oil withdrawal rate will be limited by the rate at which the water leak, if not supplanted or supplemented by intentional fluid injection,

keeps the oil level at the pump suction or at the top of the vent hole. Particularly in the initial stages of a leak, and possibly throughout the entire time a leak is occurring, the water inflow rate will most likely be at a much lower rate than oil could otherwise be removed either by use of the submersible pumps or the vent hole connection.

Ideally this displacement fluid should be brine so as to minimize dissolution of the pillars in the storage chamber. As Thorns (Thorns 1994) notes however, the significant quantity of loose salt in the mine, currently, would be preferentially dissolved. There is appreciable uncertainty in relying on this loose salt, however, and some consideration should be given to possible brine sources.

Possible sources of brine are development of caverns specifically for that purpose or recovery of natural brine **from** the base of the aquifer at the top of the salt. Development of caverns for a brine source would require obtaining land and salt on the dome, construction of a pipeline and pumping facilities, cavern wells, and disposal capability, at least during the initial cavern development. The brine could probably be injected safely into the fillholes.

Use of naturally occurring brine **from** the aquifer would require land acquisition, wells, pumps, and a pipeline. A hydrologic study would need to be conducted before this option is chosen to insure that the brine removal could be accomplished at the desired rates and would not affect surface facilities. Use of naturally occurring brine may not be a feasible alternative.

Another source of fluid is water **from** Weeks Bay or the intracoastal waterway. Use of surface waters reduces the cost of installing a system by eliminating the need for wells and some piping and reducing the size of the required pumps. However, the surface waters are essentially unsaturated with respect to sodium chloride; and their use will result in a substantial amount of salt dissolution in the mine. Some dissolution of the mine pillars will occur resulting in increased subsidence, compared to brine displacement. However, this increased subsidence resulting **from** the use of unsaturated water will be minimal in both extent and time, based upon comparisons to both the Belle Isle and Jefferson Island salt mines which have been flooded.

There is an advantage to **using** unsaturated surface waters intentionally pumped into the mine rather than allowing the mine to fill with water leaking into it as discussed above. This option would still require obtaining land, and construction of a pipeline, pumping facility, and an injection well into the mine. The location of the injection well will require study to determine the location that will result in the least impact from the salt dissolution associated with injecting raw water.

#### **4.1.4 Water Leak During Conventional Drawdown**

Potentially the most consequential scenario involving **drawdown** would occur if a major leak developed into the storage chamber during a conventional **drawdown** (mine at essentially zero pressure with all the pumps in the Service Shaft sump) **after a significant amount of the oil had been removed**. In this event, a large quantity of water, approximately equal to the amount of withdrawn oil, could flow into the mine before an increase in the mine pressure would slow the inflow rate. The Service Shaft submersible pumps and the emergency **drawdown** pumps would not be usable for **drawdown** as the intakes would be flooded with brine. The large amount of water flooding into the mine

would result in the development of a large channel which would permit oil to readily flow out of the mine once the mine pressure **equalized** with the ground water hydrostatic pressure.

Response to such a scenario would depend upon configuration of the mine when it occurred. If a source of brine or water had been developed (4.1.3) the leak inflow would be lessened by injecting water or brine into the mine, and oil withdrawal could then resume via the vent hole. If no alternate fluid source had been developed, oil withdrawal would be delayed until the mine pressurized due to the leak. Oil withdrawal could be done either by connecting the vent hole to the St. James pipeline and allowing the oil to flow out under hydrostatic pressure or by using pumps stationed below the Service Shaft manifold, if they had been previously positioned there and not relocated during the **drawdown** (3.1.3) In either case, the withdrawn oil should be replaced with intentionally injected water/brine in order to minimize the leak inflow. If there is no developed source of water/brine, oil withdrawal could occur only at the rate of water leakage, and the leak into the mine would continue to enlarge with a corresponding increase in the rate and likelihood that oil would leak out of the mine into the overlying aquifer.

#### **4.1.5 Abandonment**

A brine or water source would be useful not only if water is leaking into the mine, requiring that the oil be removed, but also at such time as the mine is finally abandoned as a storage site. The brine or water would be used to remove as much oil as possible off the floor and walls of the mine. The brine or water would also provide increased long-term **stability** for the mine, reducing ongoing surface subsidence and the potential for eventual leak development, or the possibility of mine collapse.

#### **4.1.6 Disadvantages to Pressurizing the Mine**

The disadvantages of operating the mine in a pressurized mode relate to personnel safety and maintenance of the submersible pumps. Both concerns require a safety assessment of possible impact before the mine can safely be operated at an increased pressure.

With the oil storage chamber under pressure, the oil pressure head will be above the bulkheads in the mine. A leak in the piping system or any of the oil isolation bulkheads would result in oil spilling into the **manway**, a condition which is potentially hazardous and difficult to cleanup. This condition already exists to a limited extent when the site is pumping oil to St. James or for recirculation through the fillholes. The concern can be mitigated to some extent by isolating the piping in the manifold room from the pump columns by either keeping the valves on top of the pumps shut (which is normal procedure) or disconnecting the piping and installing blind flanges. Similarly, the nitrogen **injection/equalization** piping would need to be isolated from the penetrations in the various bulkheads.

Maintenance of the pumps requires periodic running of the pumps as well as occasional removal of the pumps for repairs. The pumps probably can be operated when the mine is pressurized if the motor lubricating oil system is pressurized and the piping is not disconnected. Removal of the pumps for repairs would require that the mine be depressurized and the pumps removed as they are presently. Should the mine become

pressurized as a result of a water leak. it will **not** be **possible** to remove the **pumps** for maintenance.

## 4.2 MINE MAINTENANCE

### 4.2.1 Monitoring

There are a limited number of mine parameters that can be monitored effectively. The brine levels in the **fillhole** sump and the Service Shaft sump are presently monitored. Additionally the oil/gas level at the Service **Shaft** is also monitored as are the pressures at each of the oil isolation bulkheads and the vent hole at the surface. These are discussed early under Mine Diagnostics.

### 4.2.2 Maintenance Grouting

Grouting at Weeks Island is presently undertaken as needed in the **shafts** and the accessible **manway**. Grouting of leaks in the mine has been quite effective in stopping water inflow, for at least short periods of time. The ability to grout the shafts and the **manway** level should be maintained and exercised as needed to control leaks as they develop in these areas. The flexibility achieved by an outside standby grouting contractor is needed even if routine grouting is performed by an in-house crew.

Although not currently performed, an additional grouting task that may be needed is the grouting of the peripheries of all bulkheads in the **manway**. The Markel Mine isolation bulkheads were peripherally grouted after construction. Others may have but no records exist. As grouts age and minor salt movement occurs, occasional regrouting may be required. This will become more important if the oil isolation bulkheads are operated under pressure. It may also be important to grout the bulkheads prior to oil pressurization to avoid wetting the surfaces with oil.

The capability to grout from the surface has not been developed at Weeks Island, although the concept has been maintained in the scope of the emergency grouting contract. Grouting was conducted **from** the surface over the Wet **Drift** **after** the wet zone was first encountered, and the leak rate was high. This grouting appears to have had at best a short term effect in reducing the leak into the Wet Drift. With the development of the sinkhole and the numerical modeling that indicates that fractures may be developing into the storage levels of the mine, a study of the feasibility and effectiveness of grouting from the surface should be initiated. This study may lead to recommendations of means to control the leak(s) rather than stopping them. However, successful grouting will require definition of the leak location. The requirements of surface grouting are described more fully above (3.2 Grouting).

## 5. CONCLUSIONS

This study was initiated in response to the request by the Project Management Office to update a 1985 SPR Risk Assessment of Weeks Island geotechnical concerns. All previous recommendations have been reviewed and much new information and data have been obtained and analyzed. The conclusions that are drawn are necessarily based on the view developed from all information as of August 1994. Most significantly, (1) the sinkhole has continued to enlarge, (2) increased brine inflow into the fill hole area is observed, (3) dilatant zones in the salt are predicted from analyses, (4) the water table may be observed to be depressed immediately below the sinkhole, (5) there is a low seismic velocity channel mapped below the top of salt, (6) there is a sediment-filled crevasse located 72 feet below the top of salt, (7) there is water/brine moving downward at approximately one foot per day, and sediments moving downward at approximately one inch per day in the crevasse 72 feet below the top of salt, (8) there is a general correlation between volumes leached (sinkhole **fill**), brine inflow, and measured downward fluid velocity, (9) since early 1992 the isotopic composition of brine in the till holes has been evolving toward that of ground water sampled over the salt dome, and (10) there is historical experience with sinkholes resulting from mine leakage elsewhere.

From this information, a consistent and logical conclusion is that **there exists a leak into the mine through the salt below the sinkhole. Individual observations in most cases could be separately caused by other underground phenomena. For example, an increased brine inflow into the fill holes could be a transient phenomena associated with floor heave, or salt creep (the precise geometry of the floor is not known due to small amounts of leaching since the mine was shut in). The sinkhole could theoretically be caused by leaching of the top of the dome by fresh water flowing over the dome or down a natural trough in the top of the dome. Downward flow of water/brine 72 feet below the top of salt in a sediment filled crevasse is observed. This observation is difficult to explain, given that the top of salt was accurately mapped at four locations around the sinkhole and found to be approximately level. The simultaneous occurrence of alternate scenarios required to produce the current sequence of observed events is assessed to be sufficiently remote that a leak into the mine can be concluded.**

The only data not directly indicating a leak is the lack of an indication of tracer dye in the fill hole brine samples. However, the downward velocity measured in the water/brine of 1 foot per day in the crevasse where much of the dye was injected, and the total additional distance of about 300 feet to the mine from the injection point leads to the expectation of at least several months before dye could be expected in the fill holes. (It is anticipated, however, that the downward velocity of the brine/water increases with depth since the cross sectional area of the leak is anticipated to be smaller with depth, due to the diminished solutioning as the water/brine becomes more salt saturated. Modeling supports this premise, but crosswell data in the first 15 feet of salt is inconclusive on this point. Additionally, the time required to transit from the entry point in the mine to the fill hole area sample location is **difficult** to estimate, but may be appreciable depending on path.)

With the principal conclusion that there is currently a water/brine leak into the oil storage levels in the vicinity of the sinkhole, other conclusions follow:

1. **Continued water inflow into the mine creates a risk for uncontrolled water inflow and potential displacement of oil to the sediments above the salt or surface, causing environmental damage and oil loss.**
2. **Mitigation of the water intrusion may be feasible; however, success of mitigative techniques is not assured, may be temporary and/or expensive due to mine inaccessibility.**
3. **Based on salt structure stress created by mine subsidence, and experiences of at least one other mine, additional sinkholes can be expected in the future.**
4. **Changes in the underground operations can reduce the ongoing risks or of a major accident or event occurring.**
5. **It may be very important to maintain a fluid-filled mine, even during drawdown, to assure control under leak scenarios.**
6. **With current technology, the ability to grout a leak in the oil storage levels from the surface may be limited.**
7. **The Markel Mine maintenance and inspections are not directly related to the sinkhole concerns, but are important for long-term oil storage.**
8. **All previously identified major geotechnical risks have been mitigated; some minor recommendations were not addressed.**

These conclusions make it clear that continued oil storage will require additional effort in terms of operational changes, monitoring, etc. Since many of the changes require engineering designs, or major system configuration changes, time may be extremely important. There is much ongoing data collection, some of which will provide a better assessment of the seriousness and time urgency of the situation. An ongoing diagnostics program is currently underway with the express purpose of understanding the potential of the existing leak, and of detecting any other impending leak conditions.

## 6. RECOMMENDATIONS

The conclusions summarize the assessed status of the Project. As requested by the Project, recommendations were developed which, if implemented, will address the need for and the possible leak mitigation actions, and to provide better future leak detection.

1. **Maintain the mine fluid-filled, even during **drawdown** unless a washout can be prevented or otherwise controlled.**
  - **Develop a water or brine source sufficient to support oil **drawdown** (4.1.3, 4.1.4)**
  - **Develop a brine disposal capability **sufficient** to support oil transfers in (4.1.3)**
2. **Change the mine operation to accommodate pressurization (3.1.3)**
  - **Conduct a Safety Assessment of increasing the mine pressure (4.1.6)**
  - **Pressure the mine to about 120 psi (3.1.1)**
  - **Reposition some or all of the main withdrawal pumps (3.3.1)**
  - **Upgrade any necessary equipment in the manifold room to support pressurized operation (3.1.3)**
3. **Continue and improve water entry diagnostics**
  - **Fully analyze the mine strapping data (2.2.2)**
  - **Continue the follow on diagnostics effort**
  - **Refine the current water entry monitoring procedures (2.2)**
  - **Fully implement the program for inspection for new surface sinkholes (2.5.1)**
4. **Reinstate inspections of the Markel Mine to support long-term oil storage**
  - **Initiate a maintenance program (2.5.2)**
5. **Develop and implement leak stabilization or reduction actions, specifically brine injection, and surface grouting when leak sources can be near positively located. (It is important to note that brine injection was initiated in August 1994, and a grouting plan is nearly complete.)**
6. **Investigate the feasibility of leak detection via piezometers and flowmeters, i.e., water table changes.**

It is anticipated that the Project will critically review these recommendations and implement those recommendations consistent with its overall long term storage program.

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